Review and prospect of soil compound erosion

YANG Wenqian[1,2], ZHANG Gangfeng[1,2,3], YANG Huimin[4], LIN Degen[5,6], SHI Peijun[1,2,3,6*]

[1] State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China;
[2] Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China;
[3] Academy of Disaster Reduction and Emergency Management, Ministry of Emergency Management and Ministry of Education, Beijing Normal University, Beijing 100875, China;
[4] College of Land and Tourism, Luoyang Normal University, Luoyang 471934, China;
[5] School of Business, Wenzhou University, Wenzhou 325035, China;
[6] Academy of Plateau Science and Sustainability, Qinghai Normal University, Xining 810016, China

Abstract: Soil erosion is one of the most serious environmental issues constraining the sustainable development of human society and economies. Soil compound erosion is the result of the alternation or interaction between two or more erosion forces. In recent years, fluctuations and extreme changes in climatic factors (air temperature, precipitation, wind speed, etc.) have led to an increase in the intensity and extent of compound erosion, which is increasingly considered in soil erosion research. First, depending on the involvement of gravity, compound erosion process can be divided into compound erosion with and without gravity. We systematically summarized the research on the mechanisms and processes of alternating or interacting soil erosion forces (wind, water, and freeze-thaw) considering different combinations, combed the characteristics of compound erosion in three typical regions, namely, high-elevation areas, high-latitude areas, and dry and wet transition regions, and reviewed soil compound erosion research methods, such as station observations, simulation experiments, prediction models, and artificial neural networks. The soil erosion model of wind, water, and freeze-thaw interaction is the most significant method for quantifying and predicting compound erosion. Furthermore, it is proposed that there are several issues such as unclear internal mechanisms, lack of comprehensive prediction models, and insufficient scale conversion methods in soil compound erosion research. It is also suggested that future soil compound erosion mechanism research should prioritize the coupling of compound erosion forces and climate change.

Keywords: soil compound erosion; soil erosion; gravity erosion; wind and water erosion; freeze-thaw erosion

1　Introduction

Soil erosion is one of the most serious eco-environmental disasters. In recent years, increasing atmospheric carbon dioxide-induced global warming has been altered the global distribution of heat and water, leading to an increase in the intensity and spatial extent of global soil erosion (Guo et al., 2019; Pal et al., 2021). Soil is the major carbon reservoir of terrestrial ecosystems, and soil erosion notably impacts soil organic carbon storage, which in turn affects the carbon cycle of terrestrial ecosystems and influences regional and global climate changes (Lal, 2003; Fiener et al., 2015). Severe soil erosion can lead to soil degradation and reduce agricultural production (Tsymbarovich et al., 2020), further affecting food security and seriously threatening

the environment and human society (Betela and Wolka, 2021).

As a serious global ecological issue, soil erosion has been investigated from various research perspectives. Previous studies have focused on the intensity, extent, process, mechanism, and prediction of soil erosion (Kong et al., 2022; Wei et al., 2023; Zhu et al., 2023). In recent years, with improvements in the understanding of the mechanisms and processes of single-force erosion, concerns have gradually shifted to multi-force erosion processes (i.e., compound erosion) (Zheng et al., 2019). Compound erosion is the process of the alternation or interaction among multiple erosion drivers under natural conditions, and the impact area and degree are usually greater than those of single-force soil erosion. In a changing climate, the complexity and intensity of compound erosion processes are increasing, resulting in severe environmental problems (Guo et al., 2019). Therefore, it is a key global environmental issue with potentially major, wide-ranging interdisciplinary impacts on the food security and ecosystem viability (Betela and Wolka, 2021), loss of nutrients and soil organic carbon sequestration (Fiener et al., 2015), soil fertility and land productivity (Horvat et al., 2021), and society, economy, and infrastructure (e.g., railways and electricity towers) (Tsymbarovich et al., 2020; Feeney et al., 2022). After reviewing the literature of the past three years (2020–2022), we found that soil erosion research has focused on wind erosion, erosion process, universal soil loss, erodibility, models, and other aspects (Fig. 1). Research on the mechanism of soil erosion, numerical simulation and prediction, and the assessment of soil erosion risk are major tasks in soil and water conservation and ecological management. An accurate understanding of compound erosion mechanisms and processes is of great scientific value and a technological priority for sustainable development.
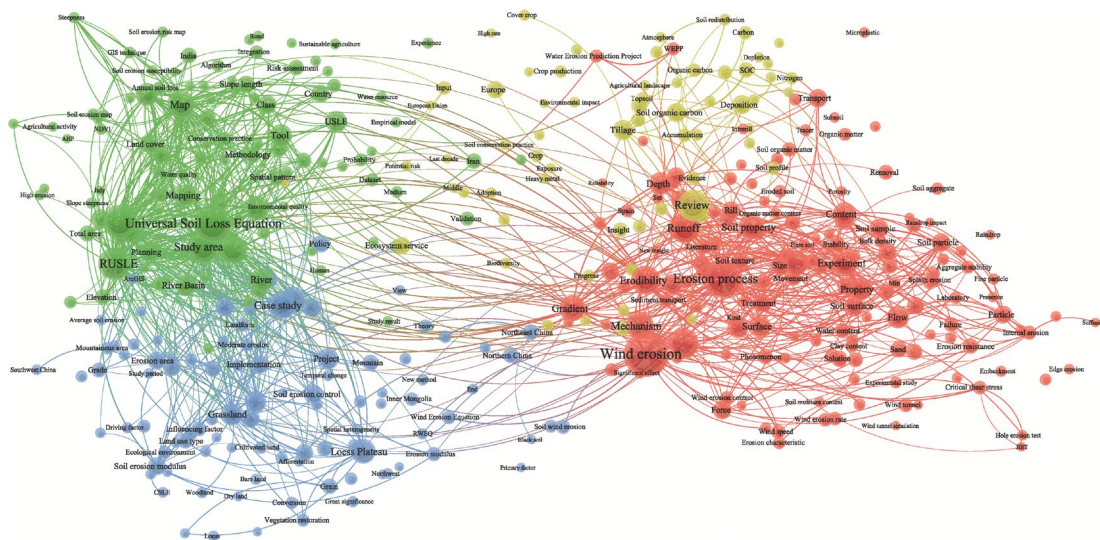

Fig. 1   Keyword cluster analysis of the literature regarding the theme of soil erosion

By reviewing existing compound erosion research, in this study, we explored specific scientific issues that must be addressed, attempting to bridge the knowledge gap in previous studies, and outlined supplements and improvements in the field. Specifically, we explored the shortcomings of existing research in depth and proposed improvement directions, aiming to provide new insights and countermeasures for soil erosion prevention and control in a changing climate.

2   Studies on soil compound erosion

Soil compound erosion is a process of soil denudation, destruction, separation, transportation, and deposition under multiple erosion forces (i.e., wind, water, gravity, and freeze-thaw action) (Zhang et al., 2019). The energy supply and material source of each erosion force are coupled, forming a completely different erosion, transportation, and deposition process than single-force

erosion. Due to the complex combination of multiple forces and the influences of subsurface factors such as topography, soil, vegetation, and land use, compound erosion exhibits distinct spatiotemporal and geographical variability (Zhao et al., 2016). Common forms of compound erosion include wind and water compound erosion, freeze-thaw and water compound erosion, and freeze-thaw, wind, and water compound erosion, most of which exhibit a certain periodicity (Assouline et al., 2017). As a special external force, gravity usually occurs with other external forces and causes large-scale soil movement. Researchers have often ignored the gravity erosion process and focused on compound erosion as a result of the alternating or interacting effects of wind, water, and freeze-thaw processes. To distinguish from other classification forms, here, we classified compound erosion into two types according to the dominant forces causing soil erosion (Table 1).

Table 1　Types of compound erosion based on the dominant forces

Number of forces	Type of compound erosion without gravity	Type of compound erosion with gravity
Two forces	Wind and water; freeze-thaw and wind; and freeze-thaw and water	Wind and gravity; water and gravity; and freeze-thaw and gravity
Three forces	Freeze-thaw, wind, and water	Wind, water, and gravity; wind, freeze-thaw, and gravity; water, freeze-thaw, and gravity
Four forces		Wind, water, freeze-thaw, and gravity

2.1　Two-force compound erosion

2.1.1　Wind and water compound erosion

The area prone to wind or water erosion is approximately 2.37×10^7 km^2, accounting for 17.5% of the global land area (Bullard and Mctainsh, 2003). Wind and water compound erosion is the result of the joint or alternating action of wind and water forces acting on the same erosion object. The forces can be subject to either dynamic or medium coupling (Yang et al., 2016). Dynamic coupling indicates that multiple external forces simultaneously occur. This term emphasizes the type and number of forces acting and their interaction (e.g., "storms"). During a storm, wind acts on precipitation, and these two forces interact and occur simultaneously (Cong et al., 2019). Medium coupling is the alternate or superimposed occurrence of different forces resulting in erosion. This term highlights that different forces act on the same medium, but there is asynchrony over time. For example, the soil within a certain area in northern China is subject to wind erosion in spring and water erosion in summer. These two forces act on the same area, but the time may alternate or overlap, which yields a more complex process due to the asynchrony in the timing of the two forces (Yin et al., 2022).

Indoor wind tunnel and rainfall experiments have shown that preceding wind erosion alters the surface microtopography, forming sand ripples and wind erosion dents. Although sand ripples can easily absorb rainfall, they also affected the runoff path in the subsequent water erosion process. As a result, slope runoff convergence is accelerated, which increases the slope runoff velocity and reduces the flow resistance, thereby enhancing runoff erosion and transport capacity (Tuo et al., 2016; Zuo et al., 2021). In contrast, preceding water erosion can result in the formation of a crust atop the topsoil layer, inhibiting subsequent wind erosion (Yang et al., 2017). At the catchment scale, wind and water compound erosion is characterized by the transport and deposition of surface materials through flowing water, which provides the material for wind erosion, while wind erosion-related transport and accumulation provide the material source for flowing water, and the coupling of these two processes intensifies the soil erosion severity (Harvey et al., 2001). With the increasing area of wind and water compound erosion, the land use change caused by human activities also significantly impacts the compound erosion intensity (Pal et al., 2021). The understanding of wind and water compound erosion mechanisms has been gradually improved.

2.1.2　Freeze-thaw and water compound erosion

Previous studies on the effect of freeze-thaw cycles on water erosion started early. Scholars have

found that the erosion amount after freeze-thaw cycles is significantly greater than that in the absence of freeze-thaw cycles under the same flow, slope, and moisture content conditions (Ferrick and Gatto, 2005). Long-term field observations have revealed that freeze-thaw action significantly increase the erosion amount in gullies, especially in gully sidewalls (Barnes et al., 2016).

In China, studies have revealed that water erosion processes and their parameters change with different freeze-thaw conditions (Wang et al., 2022; Liu et al., 2023). Through indoor experiments, researchers have determined that the effect of freeze-thaw cycles on water erosion is mainly reflected by the change in soil properties and inhibition of infiltration (Zhang and Liu, 2018). Before the thawing period, the freezing depth, initial water content, and the number of freeze-thaw cycles are the main factors affecting the soil separation capacity (Sun et al., 2018; Sun et al., 2019). If the initial water content is high, the amount of transported water increases, which enhances the freeze-thaw degree and directly cause soil structural damage, resulting in a decrease in the bulk density and an increase in the porosity (Wang et al., 2018). Under the same initial moisture content, with increasing number of freeze-thaw cycles, the aggregate stability varies. Larger aggregates (>2.00 mm) show a decreasing trend, while smaller aggregates (<0.50 mm) show an increasing trend (Edwards, 1991; Niu et al., 2020). The cohesion between soil particles is gradually destroyed, and soil particles are rearranged, thus loosening the soil structure and increasing the soil erodibility (Liu et al., 2023).

At the catchment scale, under low runoff, the freeze-thaw process tends to transform rills into gullies and increases the erosion rate at the gully head (Liu et al., 2017). Under high runoff, freeze-thaw-induced loose deposits are transported, and water erosion increases (Nadal-Romero et al., 2008). This process leads to the loss of humus and organic matter at the soil surface, which causes water redistribution in the soil profile, and also results in changes in soil freezing and thawing (Cheng et al., 2018). In summary, freeze-thaw action aggravates the water erosion intensity, and the water erosion process in turn affects the freeze-thaw intensity, and these two processes generally occur simultaneously or alternately.

2.1.3 Freeze-thaw and wind compound erosion

Freeze-thaw and wind compound erosion refers to the erosion caused by the destruction of the soil microstructure under freeze-thaw action. The influence of freeze-thaw cycles on wind erosion largely depends on the number of cycles, temperature differences, and soil moisture content before the freeze-thaw cycles (Wang et al., 2014; Liu et al., 2017). This action alters the soil physical and chemical properties, destroys the original connections between soil particles, reduces the cohesion force, and generates a loose structure, thus lowering the resistance to wind erosion (Bullock et al., 2001). With increasing number of freeze-thaw cycles, the wind erosion amount is significantly larger in thawed soils than in frozen soils (Wang et al., 2014). At the same time, the larger the temperature difference, the more severe the freeze-thaw action and the more serious the resultant soil structure damage, resulting in an increase in the wind erosion intensity (Xie et al., 2016). In addition, soil moisture increases the soil resistance to wind erosion by increasing the cohesion between particles. Therefore, the wind erosion intensity is generally negatively related to the soil moisture content (Sun et al., 2019). However, the higher the soil water content, the greater the damaging effects of freezing and thawing on the soil structure, which benefits the subsequent wind erosion. Thus, the relative contribution of the soil moisture content to wind erosion and the freeze-thaw degree should be separately analyzed.

Researchers have found that there exists an exponential relationship between the number of freeze-thaw cycles and the soil wind erosion amount by establishing a statistical model for simulating freeze-thaw cycles and wind erosion in black soil (Wu et al., 2016). However, soil erosion in the freeze-thaw zone is the result of the compound force of freeze-thaw, wind, water, and gravity. Because the freeze-thaw erosion model has been established by modifying the parameters of the water erosion model, there are very few studies on the mechanism of freeze-thaw erosion or compound erosion, and a compound erosion model is lacking.

2.1.4   Two-force compound erosion studies incorporating gravity

Research on compound erosion has shown that gravity erosion always occurs with wind, water, or freeze-thaw erosion, and is the result of compound action. Studies on the soil erosion process have mostly focused on wind, water, and freeze-thaw effects, with little or no consideration of the impact of gravity erosion on the overall erosion process. However, in fact, the influence of gravity is indispensable.

At the watershed scale, water and gravity compound erosion are synchronous in time. After the occurrence of gravity erosion, loose material accumulates, and sediment is transported through slope runoff, generating a process of re-erosion (Jin et al., 2012). According to the specific situation, scholars have usually considered processes such as debris flows and landslides that combine the processes of water and gravity erosion as geological hazards, and they have analyzed their occurrence mechanisms, constructed indicators, and established prevention and control measures or evaluation criteria (Liao et al., 2018). In addition, the unique erosion phenomena produced by the combination of freeze-thaw and gravity, such as gully bank thawing-induced collapse erosion and gully slope thawing-related slide erosion, have been investigated (Jing, 2003). To date, there is no integrated classification system for these processes.

In summary, the main reasons for the lack of research on gravity erosion are as follows: first, researchers have separated gravity erosion and other erosion phenomena as independent processes, thereby ignoring the interaction between forces; second, effective models for gravity erosion process simulation are lacking, resulting in few studies on the combination with gravity erosion.

2.2   Three-force compound erosion

2.2.1   Wind, water, and freeze-thaw compound erosion

Wind, water, and freeze-thaw compound erosion is the result of the combined force of water, wind, and temperature, resulting in a completely different transport and deposition process of soil erosion from single water erosion or wind erosion.

Current research on wind, water, and freeze-thaw compound erosion focuses on the effects of freeze-thaw action on wind and water erosion. Laboratory experiments have demonstrated that freeze-thaw action can alter soil physical and chemical properties, thereby damaging the soil structure and providing a material source for wind and water erosion (Sun et al., 2020). Additionally, freeze-thaw action weakens the soil shear strength and erosion resistance, thus increasing the force of wind and water erosion and rendering the soil more susceptible to erosion by external forces (Zuo et al., 2020). Preceding wind erosion changes the microtopography, which further increases the erosive capacity of rainfall and runoff, resulting in the joint action of freeze-thaw and wind erosion, and increasing the compound erosion intensity (Sang et al., 2021).

Laboratory experiments of artificial rainfall, wind, and freeze-thaw cycles constitute the main method to study the process and mechanism of three-force compound erosion. This approach can be used to quantify the changes in sediment particles under different dynamic conditions through control experiments. The particle size composition dramatically changes under the combined effects of freeze-thaw cycles, wind, and water, creating conditions for coarse sediment transport (Zhang et al., 2021). In addition, field observations combined with geographic information system (GIS) technology have been used to analyze the seasonal interaction characteristics of soil erosion, and successfully isolate the contribution of each erosion force to the total slope erosion amount (Fu et al., 2020).

2.2.2   Three-force compound erosion studies incorporating gravity

Wind, water, and gravity compound erosion is the main erosion type in semiarid climatic zones. The interaction among these three forces in areas with a fragmented hilly and gully terrain forms a geomorphic landscape with a widely distributed aeolian morphology.

At the catchment scale, water and gravity erosion is dominated by slope-gully erosion, with an increased erosion intensity from the top of the slope to the bottom of the gully. The wind speed is

influenced by the topography, usually producing strong wind erosion zones on windward slopes or high landforms, and weak wind erosion zones on leeward slopes or in flatter areas, where deposits and sediments tend to accumulate (Zu et al., 2014). When water and gravity compound erosion occurs, deposits continuously recede, and the eroded material is transported downstream by runoff. Moreover, wind constantly transports sediment to replenish the deposits on the slopes. This interaction among wind, water, and gravity erosion processes is an important source of coarse sand recharge of the lower Yellow River. The spatial and temporal distributions of different particle sizes under the interaction of these three erosion forces have been qualitatively observed by establishing field observation stations (Tang et al., 2001).

In other three-force compound erosion studies, such as frozen stone flow and freeze-thaw mud flow dominated by water, freeze-thaw, and gravity compound erosion (Jing, 2003) and aeolian sand melt collapse dominated by wind, freeze-thaw, and gravity compound erosion (Qu et al., 2002). These erosion phenomena are common on the Tibetan Plateau, and a unique landscape pattern has formed as a result. In regard to the above compound erosion types, the action stages of the various erosion forces can hardly be distinguished, so most scholars have regarded this erosion type as a unique phenomenon.

2.3 Multiple force compound erosion

To date, studies on compound erosion rarely involve four forces acting together (Fig. 2). However, in certain typical areas such as the Tibetan Plateau and the Pisha sandstone area in Inner Mongolia Autonomous Region of China, where serious soil erosion and severe ecological degradation occur, soil erosion is often the result of the coupling of multiple internal and external forces (Chen et al., 2020). Researchers have analyzed the soil erosion process due to multiple forces in the Pisha sandstone area. In winter and spring, it has been determined that freeze-thaw erosion leads to the loosening of the top layer of the Pisha sandstone and the formation of slope skirts under gravity (Yang et al., 2003). High winds impact the exposed bedrock to produce much coarse-grained sediment stored on slopes and in gullies. Hydraulic erosion causes the transport of the preceding stored coarse-grained sediment, forming hyperconcentrated flow with a high transportation capacity, resulting in severe compound erosion (Tuo et al., 2012).

Due to the limited research methods and observation data, the complete erosion process under alternating cycles of wind, water, freeze-thaw, and gravity has not yet been analyzed as a dynamically coupled system. With the development of environmental management practices and the advancement of theories and technical methods, the study of compound erosion interaction processes and mechanisms is one of the most essential development trends in future soil erosion research.
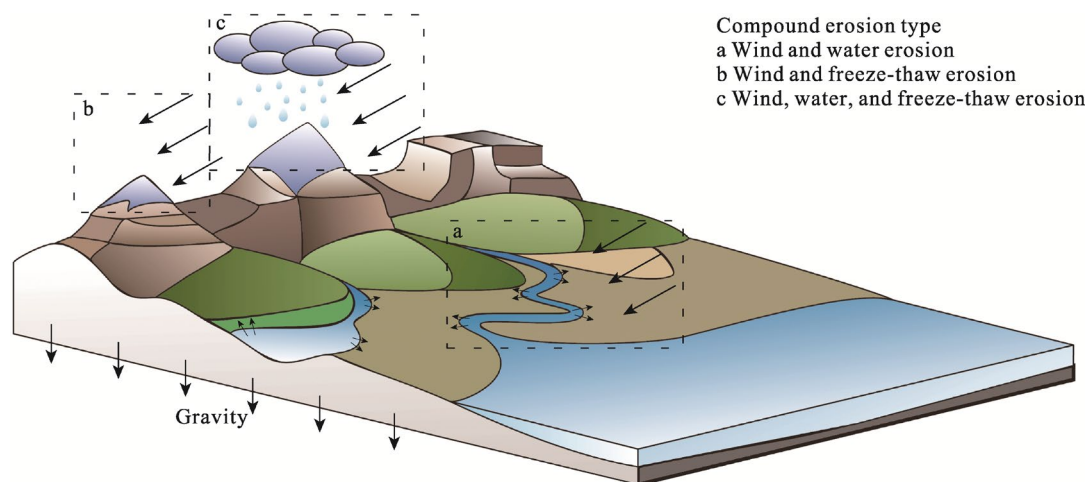

Fig. 2 Schematic diagram of multi-force compound erosion. Lowercase letters represent different compound erosion types.

2.4 Difference between the various types of compound erosion

First, gravity is used as a classification criterion. When compound erosion with gravity occurs, the following conditions are needed: first, the soil is loose or prone to sliding; second, the topsoil is unstable due to the large differences in elevation and steep slopes; third, there is a low plant cover and no artificial protection measures. Therefore, compound erosion with gravity can induce large-scale soil movement and produce serious disasters such as the destruction of arable land, burying crops, and the destruction of roads and communication facilities, river, and canal blocking and reservoir silting. Typically, compound erosion includes gravity, but in many existing studies, gravity has been excluded to investigate other compound erosion processes separately.

In addition, there are different characteristics under other combinations of compound erosion. If wind erosion is included, the main occurrence conditions include dry soil and a relatively constant wind over the surface. Thus, compound erosion that includes wind erosion mainly occurs in arid and semiarid climatic zones and in humid areas that suffer from periodic droughts. The direct consequence is a reduction in fine grains at the surface, an increase in coarse grains, and a loss of soil organic matter and nutrients. Wind erosion landforms, such as Gobi and Yardang landforms, are formed. In regard to compound erosion with or without water erosion, if this process is included, the precipitation intensity is the most important factor. Precipitation imposes the greatest effect on soil separation while also increasing the scouring and transport capacity of surface runoff. The eroded material is largely transported by runoff. This is also the main characteristic that distinguishes this process from other types of compound erosion. If freeze-thaw erosion is included, the most important factor is the cyclical negative and positive changes in temperature, resulting in soil freezing and thawing. Therefore, compound erosion involving freeze-thaw action is usually found on the Tibetan Plateau and in some alpine areas, where the ground humidity dramatically varies from day to night, freeze-thaw cycles frequently occur, and the soil swells and shrinks significantly. In summary, the various types of compound erosion are mainly influenced by the dominant forces, and they occur in different areas and exhibit different characteristics.

3 Study of compound erosion in typical areas

3.1 Compound erosion in high-elevation areas

Generally, high-elevation area is the area above 1500 m. More specifically, this area can be divided into high-elevation (1500–3500 m), ultrahigh-elevation (3500–5500 m), and extremely high-elevation (above 5500 m). In high-elevation areas, due to the large daily and annual temperature differences, there are many days with both positive and negative temperatures, resulting in frequent freeze-thaw cycles (Wang et al., 2017). This damages and loosens the topsoil structure, providing abundant sand material for wind erosion. Additionally, along with the high topography, sparse vegetation, and frequent high winds, drought conditions and strong winds occur during the same season, leading to severe wind erosion (Li et al., 2018). As a result, wind erosion often works in conjunction with freeze-thaw erosion, forming a two-force compound erosion area. At the same time, water erosion caused by rainfall and snow melt is often superimposed, causing a region where wind erosion, freeze-thaw erosion, and water erosion are jointly distributed (Zhang et al., 2003). Examples include most of the Tibetan Plateau (Chen, 2020), Greenland (Massa et al., 2012), Mexico (Montero-Martínez, 2021), and the river basin areas on the Ethiopian Plateau (Fenta et al., 2021).

Studies of compound erosion in high-elevation areas are currently in their infancy. Based on meteorological data, Yu (2021) used the Revised Universal Soil Loss Equation (RUSLE), Revised Wind Erosion Equation (RWEQ), and freeze-thaw grading evaluation model to simulate single soil erosion and estimate its intensity, and determined the distributions of water and freeze-thaw as well as wind and freeze-thaw dual-force erosion and wind, water, and freeze-thaw triple-force erosion in the Three-River Source Region (the source region of the Yangtze River, Yellow River, and Lancang River). Zerihun (2018) used the RUSLE model with GIS and remote sensing (RS)

technologies to assess the soil erosion severity in the Dembecha area, northwestern Ethiopia.

Under rapid climate change and anthropogenic disturbances, the soil erosion intensity has increased in most high-elevation areas worldwide. However, limited by the geographic environment and locational constraints, the collection of basic data in these areas is difficult, leading to fewer studies of compound erosion in these regions relative to other regions.

3.2   Compound erosion in high-latitude areas

In the geographical sense, high-latitude areas are areas between the north and south latitudes of 60° and the north and south poles of the Earth's surface. They are the coldest regions because they receive relatively low solar radiation throughout the year. Similar to that in high-elevation areas, the winter season in these regions are long and cold, with monthly average temperatures below 0°C, while the summer season is short and warm, with monthly average temperatures above 10°C. Due to the large annual differences in temperatures, these regions are prone to freeze-thaw erosion and water erosion. Examples of such areas include the black soil region of northeastern China (Zheng et al., 2019) and the agricultural regions of Canada (Aygün et al., 2021), Finland (Räsänen et al., 2023), Russia (Maltsev and Yermolaev, 2020), Siberia, and the Far East (Litvin et al., 2021). In contrast to high-elevation areas, these areas are generally flat, and most are agricultural planting areas. Unreasonable production and lifestyle patterns have led to serious soil erosion.

Compound erosion in high-latitude areas has been preliminarily studied. Sang et al (2021) analyzed the effects of freeze-thaw cycles and wind and water superposition on soil erosion on black soil slopes, and initially elucidated the slope erosion process and mechanism driven by freeze-thaw cycles and wind and water superposition. Zhang et al (2022) constructed a model to simulate the soil erosion process under the comprehensive influence of rainfall, snowmelt, and land use change in a typical watershed, and revealed the amplification effect of soil erosion under the influence of compound factors. Existing works on compound erosion in high-latitude areas are mainly focused on laboratory experiments and field observations by combining soil properties and relevant erosion indicators to simulate erosion processes and analyze the compound erosion mechanisms. However, most of the models under freeze-thaw conditions are restricted to water erosion models. Thus, the research on compound erosion processes dominated by freeze-thaw is inadequate, which further leads to insufficient numerical prediction studies in this region.

3.3   Compound erosion in wet and dry transition zones

Rainfall generally decreases from the coast toward inland areas due to factors such as the location of land and sea, sources of water vapor, and topography. The dry and wet transition zone generally refers to the intersection area of semiarid and semihumid climate types, and it is a transitional boundary zone comprising areas on both sides with an average annual precipitation of approximately 400 mm (dryness ranging from 1.49 to 1.50). In wet and dry transition zones, where multiple natural elements intersect, serious compound erosion usually occurs. Examples of such areas include the Lake Eyre and the Murray-Darling River in Australia (Bullard and McTainsh, 2003), the Sahel region in Africa (Amanambu et al., 2019), the Andes (Correa et al., 2016), and the agro-pastoral ecotone in northern China (Tong et al., 2020).

The Loess Plateau and Pisha sandstone region of China, for example, contain typical hilly and gully landscapes with high topographic fragmentation. Heavy rainfall in summer and autumn and concentrated precipitation with loose soil on the Loess Plateau result in serious soil erosion dominated by water and gravity compound erosion (Zhang et al., 2022). Fu et al (2020) revealed the seasonal variation characteristics of multi-force compound erosion in the middle reaches of the Yellow River through field observations, combined with 3D laser scanner and GIS technologies. Zhang et al (2021) documented the interactive superposition effect of multi-force erosion in the Yellow River basin by using an indoor artificial rainfall, wind tunnel, and freeze-thaw cycle solid model experiment. The freeze and water superimposed effect can amplify soil erosion by 127%, and the freeze, wind, and water superimposed effect can increase soil erosion by 164%. Yin et al (2021) used the beryllium-7 tracing technique to provide technical support to distinguish the relative effects of wind and water on compound erosion across the study region.

In summary, there are abundant studies on the mechanisms of wind, water, and freeze-thaw erosion in dry and wet transition zones of China. The mechanisms of soil erosion and the sediment yield under the combined action of various types of external forces have been clarified, and a suitable model of erosion and sediment yield has been initially established (Tang et al., 2001). Current research focuses on siltation and sedimentation, soil fertility reduction, and agroecological environment deterioration (Zhu et al., 2023). Soil erosion prevention and control has always been one of the most essential components of sustainable environmental management. As a typical soil erosion area, wind, water, and gravity compound erosion on the Loess Plateau has attracted widespread attention. Future research is needed to improve the soil and water conservation capacity and promote ecological restoration in the region.

4   Compound erosion research methods

To date, compound erosion has not been extensively studied, and relevant methods are mainly based on traditional approaches. Example include indoor experiments and model simulations. There are different research methods for different directions and issues.

4.1   Station observations and indoor simulations combined with 3D scanning technology

Traditional soil erosion research relies on establishing field runoff sites (Ke and Zhang, 2022). Generally, representative locations are selected to deploy equipment for the measurement of hydrological, meteorological, ground temperature, soil, and other parameters. Key parameters are regularly collected. By observing and measuring different rainfall intensities, subsurface conditions (vegetation type, soil characteristics, land cover, cropping system, etc.), and topographic factors (slope and slope length), researcher established a statistical relationship or model of the sediment yield resulting from compound erosion (Wen et al., 2018). This is beneficial to obtain the total amount of compound erosion and intuitively determine the characteristics of the soil surface, but the individual erosion amount of each part cannot be distinguished.

However, obtaining long-term observation data requires continuous and frequent monitoring, which requires large amounts of human and material resources. Therefore, most experiments have been conducted in the field under natural conditions and combined with indoor simulation experiments (such as simulated rainfall experiments, wind tunnel experiments, freeze-thaw cycle tests, and high-speed photogrammetry). These experiments have enabled the measurement of parameters, soil physicochemical properties, and further simulation of the compound erosion process. Through the joint use of various test devices, it is possible to simulate different compound patterns of multi-force erosion.

At the same time, 3D laser scanner technology can realistically represent the surface morphology. With the advantages of timeliness, high accuracy, and high efficiency, this technology has been widely used in monitoring soil erosion in recent years (El-Din Fawzy et al., 2020). The soil erosion amount can be quantified by scanning the morphology of the slope after the impact of multiple forces, and the indoor simulation results can be verified through field observation data. Furthermore, the contribution of each force to soil erosion can be quantified, as well as the contribution of multi-force interactions to soil erosion. Finally, the mechanism of the effect of multi-force superposition on soil slope erosion can be revealed.

4.2   Soil erosion forecasting models and remote sensing techniques

The soil erosion model is the result of theoretical research and an important tool for guiding soil and water conservation practices. There are many physical and empirical erosion models based on different forces. Example include the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965), Water Erosion Prediction Project (WEPP) (Lane and Nearing, 1989), and Chinese Soil Loss Equation (CSLE) (Liu et al., 2002) in the field of water erosion, as well as the Revised Wind Erosion Equation (RWEQ) (Rice et al., 1995), Integrated Wind Erosion Model System (IWEMS) (Anderson and Haff, 1991), Texas Model (TEAM) (Gregory et al., 2004) in the field of wind erosion. In existing studies, individual soil erosion models are usually superimposed to obtain the

total compound erosion modulus (Zheng et al., 2020). While the single-force soil erosion prediction model has been widely applied, the formation mechanisms of compound erosion remain unclear. We cannot separate the contributions of individual soil erosion processes to the total erosion. Many scholars have also proposed to establish compound erosion models, but due to the lack of relevant simulation experiments, these models have not been established. In recent years, indoor simulation experiments and outdoor monitoring of compound erosion have been widely conducted. We can modify parameters to obtain a compound model on the basis of the single-force model, which can further deepen the understanding of the compound erosion mechanism and process.

Scholars have usually combined RS techniques to accurately investigate a certain compound erosion process in field research. With the use of aerial RS data, manual visual interpretation and computer data processing are first performed to extract relevant information on the factors influencing soil erosion (Elyagoubi and Mezrhab, 2022). The soil erosion intensity in the area is then quantitatively calculated through further analysis, processing, and comparison. However, limitations on the resolution of RS images and the complexity and instability of ground conditions result in differences in the obtained soil erosion amount between images and field data.

4.3   Artificial neural networks

Compound erosion is a complex nonlinear process characterized by randomness and uncertainty. Therefore, regardless of the method used to measure the erosion intensity and erosion modulus, measurement bias can lead to inaccurate results. Scholars have successfully used a self-organizing neural network to define a soil erosion prediction model (Gholami et al., 2021). Rosskopf et al (2020) used an artificial neural network (ANN) to simulate soil erosion rates and GIS technology to characterize the spatial variation. This has confirmed the high potential value of ANN and GIS methods for soil erosion estimation and mapping. Compared to traditional regression models, ANN can better characterize the nonlinear compound processes of soil erosion and sediment yield, providing a timely approach to compound erosion research.

However, a common issue in ANN applications is that the input parameters are obtained under experimental conditions with a certain range of use, and the ANN algorithm is a black box system. Thus, its prediction mechanism remains largely unknown and cannot be linked to a specific erosion process.

5   Problems and prospects

5.1   Problems

Firstly, compound erosion involves a typical fuzzy system, but its processes and mechanisms are still not well defined. Previous research has nonlinear compound erosion processes under the interaction of multiple forces to a lesser extent. Compound erosion is a complex system in which subsurface factors, water flow, wind and sand flow, erosion materials, etc., are coupled (Fig. 3). The contributions of different forces to the total erosion according to the alternation or interaction among these forces still remain to be accurately determined, and research on the driving mechanism of multi-force erosion should be developed further.
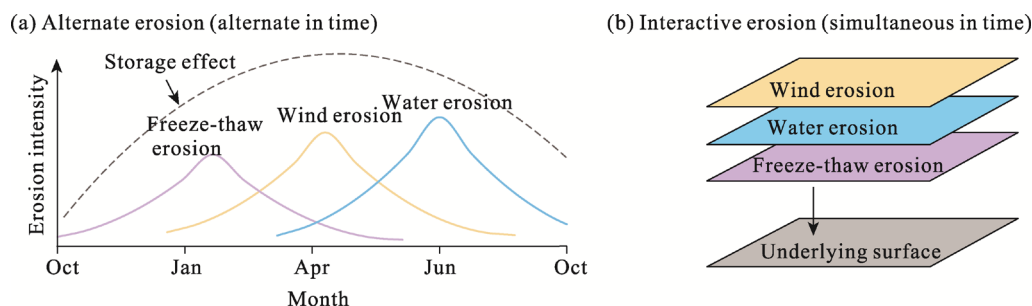

Fig. 3   Schematic diagram of alternating and interactive soil erosion

Secondly, to date, compound erosion forecasting models are lacking. Most models are still based on single-force erosion, and the superimposition analysis method has been employed to investigate compound erosion. The separate measurement of erosion forces and parameter distortion introduce high bias in model simulations due to excessively simplifying assumptions.

Thirdly, scale conversion is important for the transformation and correction of observation data at different scales and promotes a deeper understanding of the mechanisms and processes of soil erosion. Due to the complexity of processes, mechanisms and their influencing factors, as well as the available technology and funding, field observations mainly focus on smaller scales, such as slopes or runoff, rather than regional and watershed scales. The scale transformation method is usually adopted to introduce parameters or to combine the slope model with RS technique, but the error generally increases in the transformation process. Thus, improving the interconversion of data between different scales is a challenge for future soil erosion research.

Finally, climate change has substantially increased the intensity and extent of global soil erosion. Rising temperatures and decreasing wind speeds (Zhang et al., 2020) will significantly affect rainfall and land cover, leading to a sharp increase in the overall erosion rate and seriously threatening biodiversity and economic and social development. What are the trends, fluctuations, and extremes in temperature, precipitation, and wind speed under different emission scenarios? Do measures to achieve the carbon peaking and carbon neutrality goals affect the multi-force soil erosion risk? How can we reduce the environmental risk of soil erosion by adjusting the land-use structure and optimizing spatial patterns? These questions are in urgent need of in-depth research (Fig. 4).
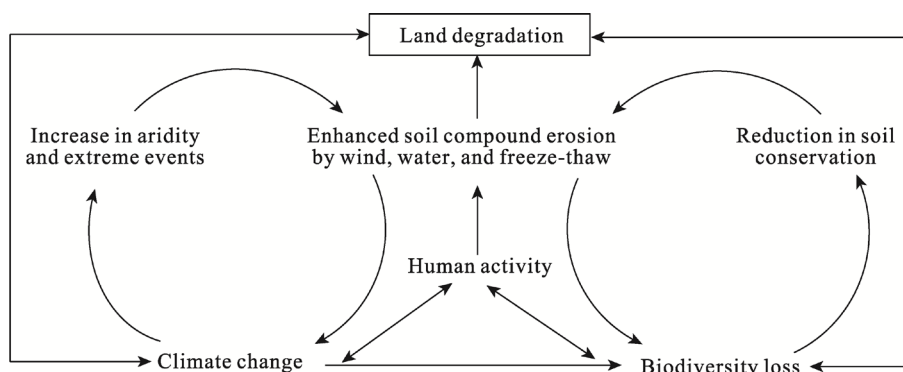

Fig. 4 Conceptual diagram of the interrelations among soil erosion, land degradation, climate change, and biodiversity loss

5.2 Prospects

Future research should consider the interaction among multiple forces in compound erosion as a completely dynamic system. The driving process, internal interactions, and mutual feedback relationship of the multi-dynamic system of compound erosion must be revealed from a physical mechanism perspective. For example, the coupling mechanism of ecosystem degradation and compound erosion under multiple dynamic stresses and the erosion mode under the interaction of multiple dynamics should be obtained. Research on compound erosion from process to mechanism can greatly enrich the content of soil erosion dynamics, ecology, and other related disciplines.

We suggest constructing multiple dynamic alternating cycle simulation techniques based on the fusion of multisource data of rainfall, wind tunnel simulations, and freeze-thaw cycles and converting single-force measurements into multi-force composite measurements. These measurements can be combined with field runoff plot observations to integrate water, wind, and freeze-thaw simulations to develop theories and technologies that support the compound erosion model to form a complete system of multi-force compound erosion model simulation technology.

In terms of multi-force erosion forecasting models, the parameters of single-force models can

be modified to achieve the transition from single-force to multi-force models. For example, the soil erodibility K value in the soil loss equation can be revised to reflect the influence of the soil crust formed by water erosion on the subsequent wind erosion or to include coefficients that reflect the effects of multi-force interactions on the entire watershed. These adjustments can help to transform single-force models into composite multi-force models.

We propose to strengthen the integration of multidisciplinary and interdisciplinary research efforts and incorporate new theories, methods and computer simulation, RS, GIS, and other technologies into scale conversion research. On the theoretical basis of existing theories and practical information, we can draw on ecological scale conversion methods or we can construct cross-scale analysis models and choose suitable scale conversion methods to adapt compound erosion models from small to large scales.

We suggest deepening the research on soil erosion control and risk prevention in different vulnerable areas to adapt to global climate change. High-resolution climate data resulting from model downscaling under future climate change scenarios can be used and combined with a multi-force compound erosion model to simulate and predict the future multi-force (precipitation, wind, and freeze-thaw action) compound erosion intensity and analyze compound erosion trends under different future climate change scenarios.

6   Conclusions

Soil erosion is one of the most serious eco-environmental disasters. Within the context of the increasing atmospheric carbon dioxide-induced global warming, fluctuations and extreme changes in climatic factors (air temperature, precipitation, wind speed, etc.) have led to an increase in the intensity and extent of compound erosion. In this study, we systematically summarized the research on the mechanisms and processes of alternating or interacting soil erosion forces under different combinations, combed the characteristics of compound erosion in three typical regions, and reviewed the research methods for compound erosion. Furthermore, we identified current problems in soil erosion research and outlined prospects. Finally, we bridged the knowledge gaps in previous studies and provided supplements and improvements to the field.

Conflict of interest

Prof. SHI Peijun is an editorial board member of Journal of Arid Land and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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Author contributions

Conceptualization: SHI Peijun, YANG Wenqian; Data curation: YANG Wenqian; Methodology: YANG Wenqian; Formal analysis: YANG Wenqian; Writing - original draft preparation: YANG Wenqian; Writing - review and editing: YANG Wenqian, ZHANG Gangfeng, YANG Huimin, LIN Degen, SHI Peijun; Funding acquisition: SHI Peijun; Resources: SHI Peijun, YANG Wenqian; Supervision: ZHANG Gangfeng, SHI Peijun, YANG Huimin, LIN Degen; Project administration: SHI Peijun; Software: YANG Wenqian; Validation: YANG Wenqian, ZHANG Gangfeng, SHI Peijun; Visualization: YANG Wenqian.

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